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## Warm Absorbing Gas in Cooling Flows

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**Abstract.** We summarize the discovery of oxygen absorption and warm ( $10^5 - 10^6$  K) gas in cooling flows. Special attention is given to new results for M87 for which we find the strongest evidence to date for ionized oxygen absorption in these systems. We briefly discuss implications for observations of cooling flows with *Chandra* and *XMM*.

### 1. Introduction

The inhomogeneous cooling flow scenario is often invoked to interpret the X-ray observations of massive elliptical galaxies, groups, and clusters. The key prediction of this scenario is the existence of large quantities of gas that have cooled out of the hot phase and dropped out of the flow. The only evidence for large amounts of mass drop-out arises from the excess soft X-ray absorption from cold gas found for many cooling flows especially from spectral analysis of *Einstein* and *ASCA* data. This interpretation is highly controversial because for systems with low Galactic columns no excess absorption from cold gas is ever found with the *ROSAT* PSPC which should be more sensitive because of its softer bandpass, 0.1-2.4 keV. Furthermore, the large intrinsic columns of cold H indicated by the *Einstein* and *ASCA* data are in embarrassing disagreement with H I and CO observations. We have re-examined the *ROSAT* PSPC data of cooling flows to search for evidence of intrinsic soft X-ray absorption and in particular have allowed for the possibility that the absorber is not cold.

### 2. M87

M87 is arguably the best target for study of its hot plasma with *ROSAT* because it is the brightest nearby galaxy, group, or cluster that also possesses an ambient gas temperature ( $\sim 2$  keV) that lies within the bandpass of the PSPC. From analysis of spatially resolved, deprojected *ROSAT* PSPC spectra we find the strongest evidence to date for intrinsic oxygen absorption and multiphase gas in the hot ISM/IGM/ICM of a galaxy, group, or cluster. When attempting to describe the 0.2-2.2 keV *ROSAT* emission of M87 by a single-phase hot plasma modified by standard Galactic absorption the best-fitting model displays striking residuals in the spectrum (Figure 1): (1) excess emission above the model for 0.2-0.4 keV and (2) excess absorption below the model for 0.5-0.8 keV. These features are apparent out to the largest radii investigated ( $\sim 100$  kpc) and cannot be attributed to errors in the calibration or the background subtraction.

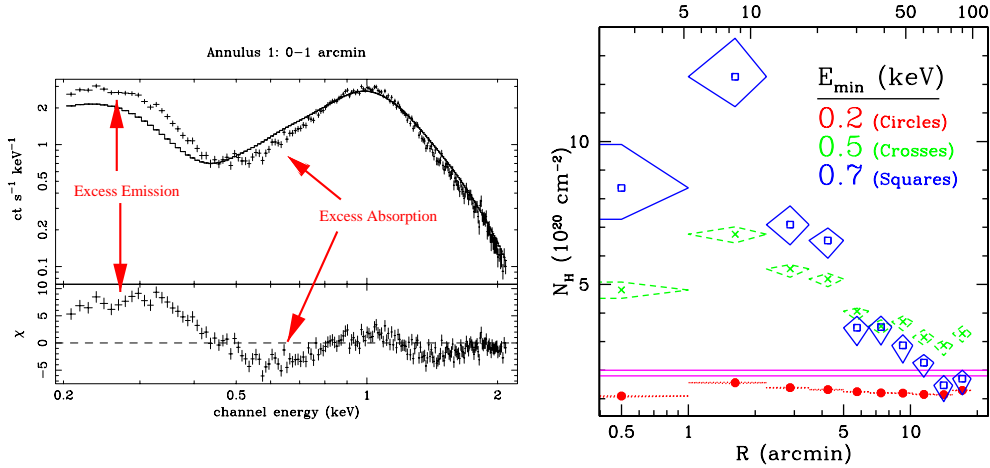


Figure 1. (Left) *ROSAT* PSPC spectrum of the the central arcminute of M87. The fitted model has hydrogen column density fixed to Galactic and Fe abundance fixed to  $0.78Z_{\odot}$ . (Right) Radial profiles of hydrogen column density of the standard foreground absorber for different values of the minimum energy of the bandpass for single-phase models. Only data with energies  $E > E_{\min}$  are included in the fits. The solid lines (magenta) indicate the range of Galactic column density. Both figures are taken from Buote (2000c).

The principal result is that the 0.5-0.8 keV absorption is consistent with that of a collisionally ionized plasma with a temperature of  $10^{5-6}$  K, where the lack of evidence of absorption below 0.5 keV strongly excludes the possibility of absorption from cold material as has been assumed in essentially all previous studies of absorbing material in cooling flows. In fact, the excess *emission* observed between 0.2-0.4 keV, which is also manifested as sub-Galactic column densities in models with standard (cold) absorbers, has a temperature that is consistent with the emission from gas responsible for the 0.5-0.8 keV absorption and could not be explained if dust were responsible for both the absorption and soft emission.

Only multiphase models can provide good fits over the entire PSPC bandpass while also yielding temperatures and Fe abundances that are consistent with results from *ASCA* and *SAX* at large radii. Both cooling flow and two-phase models indicate that the fraction of warm gas with respect to the total emission measure differs qualitatively for radii interior and exterior to  $\sim 5'$  ( $\sim 26$  kpc). For  $r > 5'$  the data are consistent with a constant (or slowly varying) fraction of warm gas as a function of radius. But for  $r < 5'$  the warm gas fraction varies from  $\sim 20\%$  within the central bin ( $1'$ ) to essentially zero within the next few bins (out to  $5'$ ).

This behavior is to be contrasted with the absorption optical depth profiles which are approximately constant with radius. It is puzzling why the oxygen absorption optical depth does not dip between  $R \sim 1' - 5'$  as would be expected if the absorption and excess soft emission arise from the same material. Perhaps this is a result of the simplifications we have employed (e.g., only assume a single absorption edge), and with rigorous consideration of the radiative transfer and the absorption from several ionization states of oxygen (and carbon and nitrogen) a self-consistent description of the multiphase medium will be obtained.

The oxygen absorption and soft emission from warm ( $10^{5-6}$  K) gas in M87 we have detected using the *ROSAT* PSPC (0.2-2.2 keV) is also able to satisfy the detections of excess emission with data at lower energies (0.07-0.25 keV) from *EUVE* (Lieu et al. 1996) and the detection of excess absorption at higher energies (0.5-10 keV) from *Einstein* and *ASCA*. Previous studies using only *EUVE* data could not decide between a non-thermal and thermal origin for the excess soft emission. Similarly, the previous detections of absorption with *Einstein* and *ASCA* could not constrain the temperature of the absorber and always assumed a cold absorber with solar abundances. Even previous studies with *ROSAT* that neglected data below  $\sim 0.5$  keV also could not constrain the temperature of the absorber (Sanders et al. 2000) because of the strong dependence of the inferred absorption on the lower energy limit of the bandpass (Figure 1).

Hence, the *ROSAT* detection of intrinsic absorption that is localized in energy (0.5-0.8 keV) is the key piece of evidence for establishing the presence of warm ( $10^{5-6}$  K) gas distributed throughout (at least) the central 100 kpc. This evidence for a multiphase ISM in M87 essentially confirms the original detection within the central  $\sim 2'$  using the *Einstein* FPCS. However, instead of intrinsic oxygen absorption Canizares et al. (1982) inferred a super-solar O/Fe ratio which does not agree with subsequent analyses of M87 using other instruments. The anomalous O/Fe ratio is probably attributed to either calibration error in the FPCS or to an underestimate of the continuum due to the absorption edges.

The total mass of the warm gas implied by the oxygen absorption is consistent with the amount of matter deposited by an inhomogeneous cooling flow. On the other hand, the mass deposition profile and the profile of warm emission fraction of the two-phase models indicate that the emission of the warm component is suppressed over  $r \sim 1' - 5'$  where the radio emission from the AGN jet clearly distorts the X-ray isophotes (Owen et al. 2000). This coincidence suggests that the AGN has influenced the hot ISM in these central regions and may have suppressed the cooling emission of the warm component (see Binney 1999). Within the central arcminute the gas has apparently readjusted and is cooling while at large radii,  $r > 5'$ , the cooling flow was not disturbed significantly by the AGN. A hybrid model of a standard cooling flow with AGN feedback seems promising for M87.

### 3. Other Cooling Flows

The highly significant detection of intrinsic oxygen absorption in the *ROSAT* PSPC data of M87 confirms the picture of a multiphase warm+hot medium in cooling flows deduced from the lower S/N PSPC data of galaxies, groups, and the cluster A1795 in Buote (2000a,b). Unlike M87 the absorption and soft emission features associated with the warm gas are not obvious upon visual examination of the lower S/N PSPC spectra of these systems (e.g., see Figure 5 of Buote 2000b), but five galaxies and groups (NGC 507, 1399, 4472, 4649, and 5044) and the cluster A1795 clearly show the same type of sensitivity of  $N_H$  to the lower energy limit of the bandpass (Figure 1). Most of these lower S/N systems also have sub-Galactic values of  $N_H$  when fitted to the entire bandpass consistent with excess soft emission like M87. Hence, warm absorbing gas appears to be common in cooling flows ranging from galactic to cluster scales.

#### 4. Observing Oxygen Absorption with Chandra and XMM

With the launches of *Chandra* and *XMM* it is an advantageous time to study oxygen absorption and warm ionized gas in cooling flows. The *XMM* (EPIC) and *Chandra* (ACIS-S) CCDs both have substantially better energy resolution than the PSPC and, unlike *ASCA*, both also have bandpasses that extend down to 0.1-0.2 keV important for measuring the emission from the warm gas.

At the moderate spectral resolution of the *Chandra* and *XMM* CCDs the absorption signature of the warm gas is expected to be a relatively broad trough over energies  $\sim 0.5 - 0.8$  keV: *thus future Chandra and XMM observations will not see a single sharp feature*. This broad feature is the result of the cumulative absorption of edges of primarily oxygen but with significant contributions from C and N (see Krolik & Kallman 1984 for a model of a warm absorber in coronal equilibrium). Perhaps the simplest means to initially quantify the warm absorption would be to show the sensitivity of  $N_{\text{H}}$  to  $E_{\text{min}}$  for a standard absorber model (Figure 1).

The grating spectrometers of *XMM* and *Chandra* have even better energy resolution (but smaller effective area) and, in principle, might detect individual absorption edges. These gratings are strictly valid only for point sources and thus will only be able to obtain spectra for the very central regions of cooling flows ( $< \sim 10''$ ). Since it is very likely that the warm absorbing gas emits over a range of temperatures and does not obey strict coronal equilibrium, the high resolution spectra offered by the gratings may detect departures from simple isothermal coronal absorption models and thus provide vital insights into the thermodynamic state of the warm gas.

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